Geotextiles and Geomembranes xxx (2009) 1–5

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Technical Note

An approach to shorten the construction period of high embankment on soft soil improved with PVD

A.K. Sinha*, V.G. Havanagi, S. Mathur

Geotechnical Engineering Division, Central Road Research Institute, Delhi-Mathura Road, New Delhi 110020, India

A R T I C L E I N F O

Article history:
Received 2 February 2008
Received in revised form
9 April 2009
Accepted 29 April 2009
Available online xxx

Keywords:
Embankment
Soft clay
Layer
Stage construction
Inflection point
Prefabricated vertical drain

A B S T R A C T

Prefabricated Vertical Drains (PVDs) are being used to accelerate the consolidation of subsoil for construction of high embankment on soft ground. The construction is carried out in stages and height of the first stage construction depends on in-situ undrained shear strength. Each subsequent stage construction is carried out after completion of either 90% primary consolidation or percent consolidation at inflection point. The height of subsequent stages depends upon the gain in undrained strength of subsoil. In this paper, the authors have advocated an approach to shorten the construction period for high embankments. In this approach, the first stage construction would be carried out based on the in-situ undrained shear strength of subsoil. Instead of waiting for 90% primary consolidation or percent consolidation at inflection point, the embankment is raised in layers of 0.2 m thickness. Based on the time required to gain strength with the construction of the 0.2 m layer, the waiting period is determined for each subsequent layers. The waiting period depends on soil parameters such as subsoil thickness, C_r/C_v ratio and different PVD factors viz. smear, drain spacing and well resistance, pattern of laying of PVD, etc. Using this approach, there would be increase in the consolidation rate and overall reduction in the construction period. A typical practical example has been solved to demonstrate the usefulness of this approach over the two conventional methods. For a 4.5 m high embankment, it is observed that waiting period is reduced by 77% and 43% as compared to the 90% primary consolidation method and inflection point method respectively.

1. Introduction

The use of vertical drains and surcharge to accelerate the consolidation of thick deposit of soft clay for soil improvement is well established and there have been a number of recent papers on this topic (Abuel-Naga et al., 2006; Abuel-Naga and Bouazza, in press; Chai et al., 2006, 2008; Chu et al., 2006; Rowe and Li, 2005; Rowe and Taechakumthorn, 2008). The significant concern for embankment construction on soft soil is to reduce the time required for consolidation of soft ground and to accelerate the rate of construction. For this purpose, PVDs are often used and several cases have been reported (e.g. Bergado et al., 1993a,b; Hansbo, 2005; Holtz, 1987; Indraratna et al., 2005; Shen et al., 2005; Tan, 1994). Analytical solutions developed by Barron (1948) and Hansbo (1981) are widely used.

Generally, construction of high embankment is carried out in stages on soft ground. Height of the first stage construction depends on in-situ undrained strength and target factor of safety. Ladd (1991) and Bergado et al. (2002) studied this aspect and analysed the stability and gain in strength of subsoil due to surcharge loading in multistage construction. Nicholson and Jardine (1981) carried out multistage loading analysis based on the assumption that consolidated undrained strength (C_U) would grow in proportion to their maximum effective vertical stress (σ'_v). An overall ratio (C_U/σ'_v) of 0.25 was selected after considering the likely effects of change to plain strain condition, anisotropy and strain rate dependence. Ladd and Foot (1974) have given SHANSEP (Stress History and Normalized Soil Engineering Properties) procedures for estimation of in-situ undrained strength. The increase in subsoil strength is estimated by carrying out vane shear and static cone penetration tests before and after the surcharge loading. Li and Rowe (2002) studied the effect of construction rates on rate sensitive soils.

The next stage of loading i.e. incremental height of embankment is taken up after completion of 90% primary consolidation (IS 15284, part 2, 2004) or at inflection point consolidation (Sinha et al., 2007). The waiting period to achieve 90% consolidation or at inflection point for soft soils may vary from few weeks to several

* Corresponding author. Tel.: +91 011 26842612; fax: +91 011 26845943.
E-mail address: sinha.crri@nic.in (A.K. Sinha).

0266-1144/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.geotexmem.2009.04.001

Nomenclature

b	Width of PVD
C_c	Compression index
C_r	Coefficient of consolidation in radial direction
C_u	Undrained shear strength of subsoil
C_v	Coefficient of consolidation in vertical direction
d	Equivalent diameter of PVD
d_s	Diameter of smear zone
D_e	Effective drain spacing
e_0	Initial void ratio
F	Factor of safety
h_1	Height of first stage embankment
h_2	Height of second stage embankment
H	Thickness of clay layer
k_r	Coefficient of permeability in radial direction
k'_r	Coefficient of permeability in smear zone (radial direction)
k_v	Coefficient of permeability in vertical direction
l	Drainage length of PVD
M	Slope of degree of consolidation with log time, $100 \times dU\%/d \log t$
M_r	Coefficient of volume change
n	Drain spacing ratio, D_e/d
N_c	Terzaghi's bearing capacity factor
P_s	Drain spacing for a square pattern
q_w	Discharge capacity of PVD
s	Smear ratio, d_s/d
S_p	Center to center spacing of PVD
S	Ultimate primary settlement
t	Time
t_b	Thickness of PVD
t_w	Waiting period in day
T_r	Time factor in radial direction
T_v	Time factor in vertical direction
U	Degree of consolidation
U_r	Degree of consolidation in radial direction
U_v	Degree of consolidation in vertical direction

Greek symbols

γ_s	Density of subsoil
γ	Dry density of embankment material
C_U	Undrained strength of in-situ subsoil
∇C_{U1}	Gain in undrained strength due to first stage construction
∇C_{U2}	Required gain in undrained strength for second stage construction
$\nabla\sigma$	Incremental over burden pressure
σ_o	Effective over burden pressure
σ'_v	Effective vertical stress

months. This period depends upon the subsoil condition, water table, spacing of PVDs and loading imposed due to embankment construction. The long waiting period not only leads to idling of man and machinery but delays the various project activities. The contractors obviously add the cost of all these delays in the project. In order to reduce the waiting period/idling time, Indraratna et al. (1992, 2005) studied the effect of loading rate of a 4 m high embankment on PVD stabilized soft clay. The rate of construction varied from 0.4 m/week to 0.1 m/week. It was concluded that slow rate of construction would allow the soft soil to gain sufficient strength supporting the stability of embankment.

In the present paper, a new approach has been proposed for incremental loading of the embankment. It has been suggested to raise the embankment in small increments of 0.2 m. Based on the time required to gain strength with construction of 0.2 m, the waiting period is determined for each subsequent layer. The method for calculating gain in undrained strength due to loading; degree of consolidation required for second and subsequent stage of loading, etc. has been explicitly explained in the paper and is supported with a solved example. It has been found that the method of small incremental loading is far more effective than the conventional approach as it not only reduce the total construction period but also reduces the idling of man and machinery.

2. Proposed construction method

The proposed construction method for high embankment has been given step wise as below.

Step 1 Height of first stage embankment construction.

The height of first stage (h_1) construction should be based on undrained shear strength of in-situ (virgin) subsoil as below.

$$h_1 = \frac{C_U N_c}{\gamma F} \tag{1}$$

where C_U = undrained strength of in-situ subsoil in kN/m^2, $N_c = 5.7$ (Terzaghi's bearing capacity factor), h_1 = height of the first stage embankment, γ = dry density of embankment material, $F = 1.25$ (IS 15284, part 2, 2004).

Step 2 Gain in undrained strength of subsoil due to first stage construction.

The gain in strength of in-situ subsoil due to first stage construction at 90% degree of consolidation is estimated using equation (2) (Nicholson and Jardine, 1981; Almeida et al., 2000).

$$\frac{\nabla C_{U1}}{\gamma h_1} = 0.25$$

$$\nabla C_{U1} = 0.25 \times \gamma h_1 \tag{2}$$

where ∇C_{U1} = gain in undrained strength of subsoil in kN/m^2 due to first stage construction, γ = dry density of embankment soil, h_1 = height of the first stage construction.

Step 3 Required gain in undrained strength of subsoil for second stage embankment construction.

According to MORTH (2001), the height of each compacted layer of embankment should be 0.2 m. For 0.2 m layers of embankment as second stage construction (h_2), required gain in undrained strength (∇C_{U2}) of subsoil is estimated by equation (4).

$$h_1 + h_2 = \frac{(C_U + \nabla C_{U2}) N_c}{\gamma F} \tag{3}$$

$$\nabla C_{U2} = (h_1 + h_2)\frac{F \times \gamma}{N_C} - C_U \tag{4}$$

Step 4 Degree of consolidation required for construction of second stage.

Assuming the gain in undrained shear strength as linear,

the required degree of consolidation can be estimated by equation (5).

$$\frac{90 \times \nabla C_{U2}}{\nabla C_{U1}} \% \tag{5}$$

Step 5 Waiting period for construction of second stage.

The waiting period corresponding to degree of consolidation evaluated in step 4 can be estimated by equation (6) (Carrillo, 1942; Barron, 1948; Hansbo, 1981).

$$U = 1 - (1 - U_v)(1 - U_r) \tag{6}$$

The vertical degree of consolidation $U_v(t)$, is given by

$$U_v(t) = \sqrt{\frac{4 \times T_v}{\pi}} \tag{6a}$$

where $U_v(t) < 60\%$ (Atkinson and Eldred, 1981).

The time factor (T_v) for vertical drainage is

$$T_v = \frac{C_v t}{H^2} \tag{6b}$$

where, H is the thickness of clay layer, t = time, C_v = coefficient of consolidation in the vertical direction.

The radial degree of consolidation $U_r(t)$, is given by

$$U_r(t) = 1 - \exp\left[\frac{-8T_r}{\mu}\right] \tag{6c}$$

The time factor (T_r) for radial drainage is

$$T_r = \frac{C_r t}{D_e^2} \tag{6d}$$

where D_e is the effective drain spacing, C_r = coefficient of consolidation in the radial direction.

$$C_r = \frac{k_r'}{m_r}\gamma_w \tag{6e}$$

$$\mu = \ln n - \frac{3}{4} + \left(\frac{k_r}{k_r'} - 1\right)\ln s + \pi\frac{2 \times l^2 k_r}{3 \times q_w} = F_n + F_s + F_w \tag{6f}$$

where, F_n = drain spacing factor, $n = D_e/d$ = drain spacing ratio, $D_e = 1.13 \times P_s$ (drain spacing for a square pattern), F_s = smear factor, $s = d_s/d$ = smear ratio, d_s = diameter of smear zone, $d = (b + t_b)/2$ = equivalent diameter of PVD (Chai and Miura, 1999), t_b = thickness of PVD, k_r = coefficient of permeability in radial direction, k_r' = coefficient of permeability in smear zone (radial direction), m_r = coefficient of volume change, F_w = well resistance factor, $q_w = 5k_r l^2$ (Bo, 2004), q_w = discharge capacity of PVD, l = drainage length of PVD, $k_r' = k_v = 1 \times 10^{-9}$ m/s (Bergado et al., 1991; Chu et al., 2002), $k_r/k_v = 3$,

A typical graph has been plotted between degree of consolidation (U) versus time (t) using equations (6)–(6f) for assumed soil and PVDs' properties such as depth of clay layer (H) = 10 m, the values of $C_r/C_v = 3$, smear ratio = 2, b = 0.1 m, t_b = 0.004 m, band drain spacing = 2 m center to center in square pattern and shown in Fig. 1. The graph has been plotted for a time interval of 5 days. Fig. 1 can be used for estimating the waiting period corresponding to the degree of consolidation estimated in step 4.

Step 6 Third stage/subsequent layers of construction.

Similarly, third stage/subsequent layers of 0.2 m thick can be completed and keeping the same waiting period as determined in step 5.

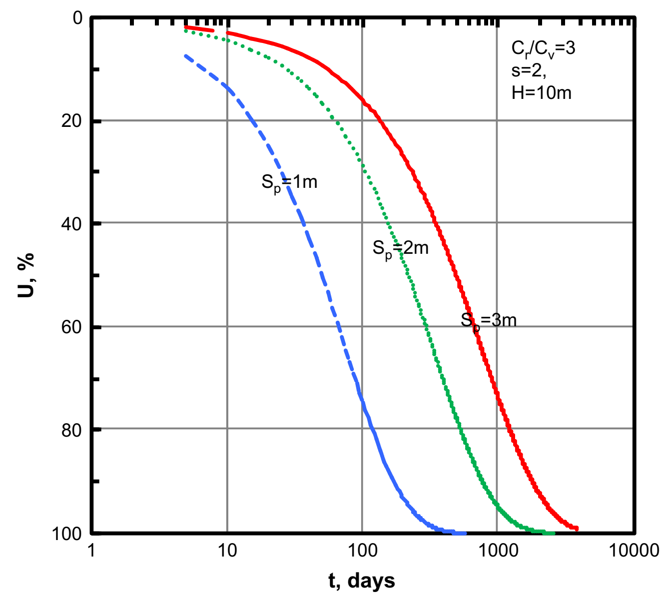

Fig. 1. U versus t (proposed method and 90% primary consolidation method).

3. 90% Primary consolidation method

In this method, first stage construction is similar to the proposed method and depends on the in-situ undrained shear strength of the virgin soil. Second/subsequent stages of construction may be carried out after completion of 90% primary consolidation (IS 15284, part 2, 2004). Similar to the proposed method, a graph is plotted between degree of consolidation (U) versus time (t) for assumed soil and PVDs' properties as shown in Fig. 1. Fig. 1 can be used for estimating waiting period for subsequent stages of construction corresponding to 90% primary consolidation.

4. Inflection point method

In this method also, the first stage construction is similar to the proposed method. Second/subsequent stages of construction may be carried out after completion of degree of consolidation at inflection point (Sinha et al., 2007). Using the equations (6)–(6f), a graph is plotted between M = slope of degree of consolidation ($100 \times dU\%/d \log t$) and time (t) for the same properties of soil and PVDs as above methods. The change in slope of the curve is determined as inflection point (Robinson, 1997) and shown in Fig. 2. The graph is plotted for a time interval of 5 days. Fig. 2 can be used for estimating the waiting period at inflection point for subsequent stages of construction.

5. Comparison of proposed construction method with other two conventional methods by typical practical solved example

An embankment of height 4.5 m is to be constructed on a soft ground of clay layer thickness equal to 10 m. The undrained strength of subsoil is $C_U = 15$ kN/m^2, compression index $C_C = 0.8$, $C_r/C_v = 3$ and initial void ratio $e_o = 2.1$. The dry density (γ) of the embankment material is 18 kN/m^3 and subsoil density (γ_s) is 15 kN/m^3. Before construction of embankment, the subsoil strata are treated with a PVDs. The width (b) and thickness (t_b) of PVD is 0.1 m

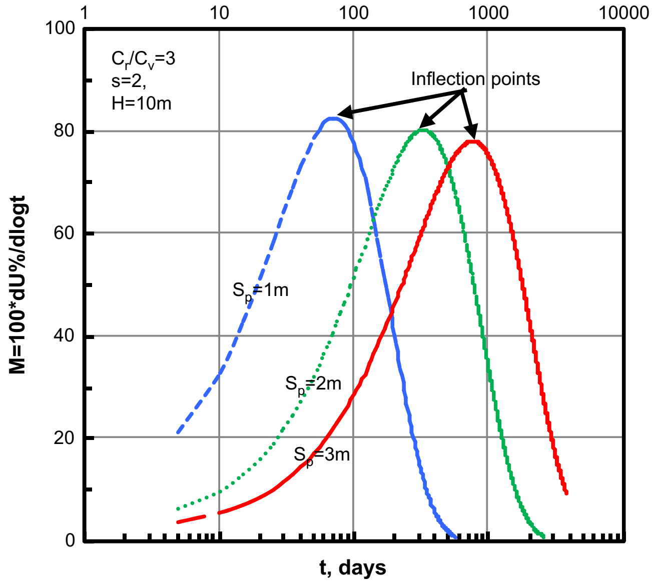

Fig. 2. *M* versus *t* (inflection point method).

and 0.004 m respectively. The spacing of band drain is 2 m center to center in the square pattern. The water table is at the top of ground surface.

Determine the required waiting period for construction of embankment by the proposed method, 90% primary consolidation method and inflection point method.

5.1. *Solution*

The total waiting period for construction of 4.5 m high embankment is determined by proposed construction method and has been compared with 90% primary consolidation method and inflection point method.

5.1.1. *Waiting period by proposed method*

Step 1 Height of first stage (h_1) construction is determined by equation (1).

$$h_1 = \frac{C_U N_c}{\gamma F} = \frac{15 \times 5.7}{18 \times 1.25}$$
$$= 3.8\ \text{m} \quad (F = 1.25 \text{ as per IS 15284, part 2, 2004})$$

So, the height of first stage embankment = 3.8 m.

Step 2 Gain in undrained strength of subsoil due to first stage (h_1) construction.

Gain in undrained strength due to first stage loading (h_1) corresponding to 90% degree of consolidation using equation (2).

$$\nabla C_{U1} = 0.25 \times 3.8 \times 18 = 17.1\ \text{kN/m}^2$$

Step 3 Required gain in undrained strength of subsoil for second stage (h_2) construction.

In the second stage construction, the height of embankment is raised by 0.2 m. For 0.2 m height of embankment construction as second stage loading (h_2), required gain in undrained strength of subsoil is estimated by equation (4).

$$\nabla C_{U2} = 0.79\ \text{kN/m}^2$$

Step 4 Degree of consolidation required for construction of second stage.

The degree of consolidation corresponding to gain in strength in step 3 is evaluated by using equation (5).

$$\frac{90 \times 0.79}{17.1} = 4.16\%$$

Step 5 Waiting period for construction of second stage (h_2).

From Fig. 1, corresponding to 4.16% degree of consolidation the waiting period is determined as 14 days.

Step 6 Third stage/subsequent layers of construction.

Similarly, third stage/subsequent layers of embankment construction may be completed in multiples of 0.2 m compacted thickness. The waiting period of each layer shall be 14 days.

Step 7 Determination of ultimate primary settlement.

The total ultimate primary settlement can be determined using equation (7) as below

$$S = \frac{H}{1 + e_0} \times C_C \times \log_{10}\left(\frac{\sigma_0 + \nabla\sigma}{\sigma_0}\right) \tag{7}$$

Considering the total primary settlement of 1.9 m and to achieve the required height of embankment of 4.5 m, the total height of construction above ground surface shall be 4.5 + 1.9 = 6.4 m. This total height of construction is carried out as first stage of construction = 3.8 m and remaining height of the embankment = 2.6 m in 13 equal layers (2.6/0.2). The total waiting period of construction is determined as 13 × 14 = 182 days.

5.1.2. *Waiting period by 90% primary consolidation method.*

Height of first stage construction may be kept same as proposed method i.e. 3.8 m.

According to this method, second stage construction may be carried out after completion of 90% primary consolidation of subsoil.

Gain in undrained strength due to first stage loading (h_1) is same as discussed in step 2 of proposed method.

$$\nabla C_{U1} = 17.1\ \text{kN/m}^2$$

Total undrained strength of subsoil = 15 + 17.1 = 32.1 kN/m^2.

Safe height for the second stage embankment construction is equal to 8.14 m using equation (1) on undrained shear strength of 32.1 kN/m^2. Ultimate primary settlement of 1.9 m is calculated using equation (7) for 6.4 m height of construction in step 7 of proposed method. Hence, the height of second stage construction is calculated as 2.6. Total height of embankment construction during second stage = 3.8 + 2.6 = 6.4 m which is less than 8.14 m. Hence, it is o.k.

Total waiting period is estimated as 780 days from Fig. 1 at 90% degree of consolidation.

5.1.3. *Waiting period by inflection point method*

The height of first stage construction is kept same as 3.8 m.

From Fig. 2, inflection point is observed to be at 320 days. Corresponding to this waiting period, the degree of consolidation is observed to be 63%. According to this method, second stage construction should be started after completion of 63% degree of consolidation of subsoil due to first stage construction.

Please cite this article in press as: Sinha, A.K., et al., An approach to shorten the construction period of high embankment on soft soil improved with PVD, Geotextiles and Geomembranes (2009), doi:10.1016/j.geotexmem.2009.04.001

Gain in undrained strength at 63% degree of consolidation is $= 0.63 \times 17.1/0.9 = 11.97$ kN/m^2.

Total undrained strength of subsoil $= 15 + 11.97 = 26.97$ kN/m^2.

Safe height for the second stage embankment construction is equal to 6.84 m using equation (1) on undrained shear strength of 26.97 kN/m^2.

Ultimate primary settlement of 1.9 m is calculated using equation (7) for 6.4 m height of construction in step 7 of proposed method. Hence, the height of second stage construction is calculated as 2.6. Total height of embankment during second stage $= 3.8 + 2.6 = 6.4$ m which is less than 6.84 m. Hence, it is o.k.

The total waiting period is estimated as 320 days from Fig. 2 at inflection point.

6. Conclusions

It is concluded that the proposed method significantly reduces the time period required for construction of an embankment compared to other two conventional methods (viz. 90% primary consolidation method and inflection point method). The findings for an example involving a 4.5 m high embankment indicate that the proposed method reduces the total waiting period by 77% as compared to 90% primary consolidation method and 43% compared to the inflection point method. Also as the embankment is raised in thin (0.2 m thick) layers, the contractor need not move the construction machinery resulting in more economical construction. It is recommended that the proposed approach may be validated by a field case study.

Acknowledgements

Kind approval of the Director, Central Road Research Institute, New Delhi.

References

Abuel-Naga, H., Bouazza, A. Equivalent diameter of a prefabricated vertical drain. Geotextiles and Geomembrane, in press.

Abuel-Naga, H.M., Bergado, D.T., Chaiprakaikeow, S., 2006. Innovative thermal technique for enhancing the performance of prefabricated vertical drain during the preloading process. Geotextiles and Geomembranes 24 (6), 359–370.

Almeida, M.S.S., Santa, P.F.L., Martins, I.S., Spotti, A.P., Coelho, L.B.M., 2000. Consolidation of very soft clay with vertical drains. Geotechnique 50 (2), 633–643.

Atkinson, M.S., Eldred, P.J.L., 1981. Consolidation of soil using vertical drains. Geotechnique 31 (1), 33–43.

Barron, R.A., 1948. Consolidation of fine grained soils by drain well. ASCE Transactions 113 (2346), 718–743.

Bergado, D.T., Alfaro, M.C., Balasubramaniam, A.S., 1993a. Improvement of soft Bangkok clay using vertical drains. Geotextiles and Geomembranes 12 (7), 615–663.

Bergado, D.T., Mukherjee, K., Alfaro, M.C., Balasubramaniam, A.S., 1993b. Prediction of vertical-band-drain performance by the finite-element method. Geotextiles and Geomembranes 12 (6), 567–586.

Bergado, D.T., Asakami, H., Alfaro, M.C., Balasubramaniam, A.S., 1991. Smear effects of vertical drain on soft Bangkok clay. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 117 (10), 1509–1530.

Bergado, D.T., Balasubramaniam, A.S., Fannin, R.J., Holtz, R.D., 2002. Prefabricated vertical drains (PVDs) in soft Bangkok clay: a case study of the new Bangkok international airport project. Canadian Geotechnical Journal 39, 304–315.

Bo, M.W., 2004. Discharge capacity of prefabricated vertical drain and their field measurements. Geotextiles and Geomembranes 22 (12), 37–48.

Carrillo, N., 1942. Simple two and three dimensional cases in the theory of consolidation of soils. Journal of Mathematics and Physics 21 (1), 1–5.

Chai, J.C., Carter, J.P., Hayashi, S., 2006. Vacuum consolidation and its combination with embankment loading. Canadian Geotechnical Journal 43, 985–996.

Chai, J.C., Miura, N., 1999. Investigation of factors affecting vertical drain behavior. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 125 (3), 216–226.

Chai, J., Miura, N., Bergado, D.T., 2008. Preloading clayey deposit by vacuum pressure with cap-drain: analyses versus performance. Geotextiles and Geomembranes 26 (3), 220–230.

Chu, J., Bo, M.W., Choa, V., 2006. Improvement of ultra-soft soil using prefabricated vertical drains. Geotextiles and Geomembranes 24 (6), 339–348.

Chu, J., Bo, M.W., Chang, M.F., Choa, V., 2002. Consolidation and permeability properties of Singapore marine clay. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 128 (9), 724–732.

Hansbo, S., 1981. Consolidation of fine grained soils by prefabricated drains. In: Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, vol. 3, pp. 677–682.

Hansbo, S., 2005. Experience of consolidation process from test areas with and without vertical drains. In: Indraratna, B., Chu, J. (Eds.), Ground Improvement – Case Histories. Elsevier, Amsterdam, pp. 3–50.

Holtz, R.D., 1987. Preloading with prefabricated vertical strip drains. Geotextiles and Geomembranes 6 (1–3), 109–131.

Indraratna, B., Balasubramaniam, A.S., Balachandran, S., 1992. Performance of test embankment constructed to failure on soft marine clay. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 118 (1), 12–33.

Indraratna, B., Sathananthan, I., Balasubramaniam, A.S., 2005. Theoretical and numerical perspectives and field observations for the design and performance evaluation of embankments constructed on soft marine clay. In: Indraratna, B., Chu, J. (Eds.), Ground Improvement – Case Histories. Elsevier, Amsterdam, pp. 51–89.

IS 15284 (part 2), 2004. Design and Construction for Ground Improvement – Guide Lines Part 2, Pre-consolidation Using Vertical Drains. Bureau of Indian Standard, New Delhi.

Ladd, C.C., Foot, R., 1974. New design procedure for stability of soft clays. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 100 (7), 763–786.

Ladd, C.C., 1991. Stability evaluations during staged construction. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 117 (4), 540–615.

Li, A.L., Rowe, R.K., 2002. Some design considerations for embankments on rate sensitive soils. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 128 (11), 885–897.

MORTH, 2001. Specifications for Road and Bridge Works. Indian Road Congress, New Delhi.

Nicholson, D.P., Jardine, R.J., 1981. Performance of vertical drains at Queenborough bypass – vertical drains. Geotechnique. Thomas Telford Ltd., London, pp. 91–160.

Robinson, R.G., 1997. Consolidation analysis by an inflection point method. Geotechnique 47 (1), 199–200.

Rowe, R.K., Li, A.L., 2005. Geosynthetic-reinforced embankments over soft foundations. Geosynthetics International 12 (1), 50–85.

Rowe, R.K., Taechakumthorn, C., 2008. Combined effect of PVDs and reinforcement on embankments over rate-sensitive soils. Geotextiles and Geomembranes 26 (3), 239–249.

Sinha, A.K., Havanagi, V.G., Mathur, S., 2007. Inflection point method for predicting settlement of PVD improved soft clay under embankments. Geotextiles and Geomembranes 25 (6), 336–345.

Shen, S.L., Chai, J.C., Hong, Z.S., Cai, F.X., 2005. Analysis of field performance of embankments on soft clay deposit with and without PVD-improvement. Geotextiles and Geomembranes 23 (6), 463–485.

Tan, S.A., 1994. Hyperbolic method for settlements in clays with vertical drains. Canadian Geotechnical Journal 31 (1), 125–131.

Please cite this article in press as: Sinha, A.K., et al., An approach to shorten the construction period of high embankment on soft soil improved with PVD, Geotextiles and Geomembranes (2009), doi:10.1016/j.geotexmem.2009.04.001